Agricultural sustainability estimation of the European photovoltaic greenhouses

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Abstract

The integration of the photovoltaic (PV) energy in the greenhouse farm has raised concerns on the agricultural sustainability of this specific agrosystem in terms of crop planning and management, due to the shading cast by the PV panels on the canopy. The PV greenhouse (PVG) can be classified on the basis of the PV cover ratio (PV_R), that is the ratio of the projected area of

PV panels to the ground and the total greenhouse area. In this paper, we estimated the yield of 14 greenhouse horticultural and floricultural crops inside four commercial PVG types spread in southern Europe, with PV_R ranging from 25 to 100%. The aim of the work is to identify the PVG types suitable for the cultivation of the considered species, based on the best trade-off between PV shading and crop production. The daily light integral (DLI) was used to compare the light scenarios inside the PVGs to the crop light requirements, and estimate the potential yield. The structures with a PV_R of 25% were compatible with the cultivation of all considered species, including the high light demanding ones (tomato, cucumber, sweet pepper), with an estimated negligible or limited yield reduction (below 25%). The medium light species (such as asparagus) with an optimal DLI lower than 17 mol m^{-2} d^{-1} and low light crops can be cultivated inside PVGs with a PV_R up to 60%. Only low light demanding floricultural species with an optimal DLI lower than 10 mol m^{-2} d^{-1}, such as poinsettia, kalanchoe and dracaena, were compatible inside PVGs with a PV_R up to 100%. Innovative cropping systems should be considered to overcome the penalizing light scenarios of the PVGs with high PV_R, also implementing LED supplementary lighting. This paper contributes to identify the sustainable PVG types for the chosen species and the alternative crop managements in terms of transplantation period and precision agriculture techniques, aimed at increasing the crop productivity and adaptability inside the PVG agrosystems.

Keywords: horticulture, floriculture, management, solar energy, light

Highlights

- The yield inside PV greenhouses was estimated on 14 species
- The evaluation identified the suitable crops inside four PV greenhouse types
- A PV cover ratio of 25% is compatible to all crops, with limited yield reduction
- A PV cover ratio of 50% is sustainable to medium and low light demanding crops
- Structures with 100% PV cover support only crops with optimal DLI<10 mol m^{-2} d^{-1}

Nomenclature

a = PAR conversion coefficient from MJ m^{-2} to mol m^{-2} for sunlight, equal to 4.57

CV = Coefficient of variation (%)

CVG = Conventional greenhouse

DLI = Daily light integral (mol m^{-2} d^{-1})

DLI_{min} = Minimum crop daily light integral (mol m^{-2} d^{-1})

DLI_{opt} = Optimal crop daily light integral (mol m^{-2} d^{-1})

f = fraction of PAR to the global solar radiation, equal to 0.48

G_{GR} = Percentage ratio of the global radiation inside a PVG compared to a CVG (%)

I_0 = Average monthly irradiation on horizontal plane (Wh m^{-2} d^{-1})

I_d = Diffuse radiation (W m^{-2})

I_D = Direct radiation (W m^{-2})

I_G = CVG average hourly global radiation (Wh m^{-2})

I_{GP} = PVG average hourly global radiation (Wh m^{-2})

S_P = Outside average daily PAR radiation sum (mol m^{-2} d^{-1})

S_{PC} = CVG average daily PAR radiation sum (mol m^{-2} d^{-1})

S_{PG} = PVG average daily PAR radiation sum (mol m^{-2} d^{-1})

LAI = Leaf area index

LUE = Light use efficiency (g C MJ^{-1})

m = Months

OP = Observation point

PAR = Photosynthetically active radiation (W m^{-2})

PV = Photovoltaic

PVC = Polyvinyl chloride

PVG = Photovoltaic greenhouse

PV_R = Photovoltaic cover ratio (%)

V_c = Mean fresh yield variation coefficient (%)

RIE = Radiation interception efficiency

ST = Standard (glass or plastic) cladding

Y_f = Average yield factor (%)

τ = Average greenhouse transmissivity

1. INTRODUCTION

The environmental sustainability of the modern agriculture is strongly linked to the implementation of different strategies aimed to reducing the use of production factors, including energy. The application of this concept to intensive greenhouse systems includes the introduction of technologies based on renewable energy sources, such as photovoltaic (PV) systems, wind turbines, heat pumps, solar panels and hybrid PV thermal systems (Agrawal and Tiwari, 2015; Hassanien et al., 2016). Within the PV energy applications to protected agriculture, the PV greenhouse (PVG) is an agrosystem potentially able to combine food and energy production on the same land unit by integrating the PV systems on the greenhouse roof. The consequent main advantages are the diversification of the farmers' income and the higher competitiveness and rural multi-functionality of the PVG farm (Marcheggiani et al., 2013; Tudisca et al., 2013).

Despite these principles that inspired the emergence of PVGs, most structures were built in marginal agricultural lands with an excessive percentage of the roof covered with PV panels. The only purpose was to maximise the PV energy production and speculate on the related income deriving from the high public subsidies, regardless of the crop light requirements (Cossu et al., 2014; Fatnassi et al., 2015). In some European countries such as Italy and France, the current regulations often prohibit the installation of ground-based PV systems in agricultural areas, due to environmental problems including soil sealing and landscape and biodiversity deterioration (Colantoni et al., 2015; Delfanti et al., 2016; Fatnassi et al., 2015). Under these circumstances, the PVG was considered a solution to bypass the current laws, by installing the PV systems on new and cheap rural buildings, such as greenhouses, specifically built for the purpose (Castellano, 2014; Marucci et al., 2018). In addition, the speculative construction of numerous PVGs in Southern European countries will require regional and national regulatory frameworks to manage the PV waste management and recycling of the high amount of PV panels at the end of their life cycle.

The agricultural sustainability of the PVGs can be defined as the optimal trade-off between energy and crop production, aimed to maximise the greenhouse crop productivity, on the basis of the actual light conditions. In fact, the shading of the PV panels on the greenhouse area affects yield, growth and development of the plants. As a result, the PVG farm can achieve a higher resource and energy use efficiency and reduce the competition for the land resources (Cuce et al., 2016; Dinesh and Pearce, 2016; Yano et al., 2010).

The cumulated global radiation inside PVGs decreases as a function of the increasing PV cover ratio (PV_R), that is the ratio of the projected area of PV panels to the ground and the total greenhouse area. This reduction was found to be equal to 0.8% for each 1% increase of the PV_R, as the average of the main commercial PVG types in Europe (Cossu et al., 2018). The main design criteria for the future generation of PVGs include a PV_R limited to values around 20%, the use of semi-transparent or organic PV technologies, the installation pattern of the PV panels on the roof (such as the checkerboard pattern), the increase of the greenhouse height, the orientation to North (N)-South (S) instead of East (E)-West (W), or the use of the PV energy to power electrical appliances for microclimate control (Al-Shamiry et al., 2007; Emmott et al., 2015; Fatnassi et al., 2015; Minuto et al., 2009; Yano et al., 2014, 2009). Some crops require moderate shading during their cycle and the semi-transparent PV panels can be used to provide it during periods of intense irradiation through dynamic PV systems, able to adjust the tilt of the PV modules according to the crop light needs (Li et al., 2018; Marucci and Cappuccini, 2016; Moretti and Marucci, 2019a). All these technical solutions are targeted to optimize the energy and the agricultural production by varying the shading of the PV panels at canopy level and the impact on the greenhouse farm in terms of energy consumption (Moretti and Marucci, 2019b). However, a currently open issue concerns the existing PVGs with high PV_R (from 50 to 100%), for which technical and agronomic solutions are required to establish a balance between energy and food production (Castellano et al., 2016; Kadowaki et al., 2012; López-Marín et al., 2012; Scognamiglio et al., 2014). For example, in Italy the current regulations impose an economic target to PVG farms, in which the income of the crops should be equal or higher than that deriving from the energy injected to the grid (Agenzia delle Entrate, 2009). The income of PVG types with high PV_R is currently unbalanced towards the energy production, and the difficulties related to cultivation pose a debate on whether these PVGs can be actually considered agricultural greenhouses or power plants where most crops are precluded.

The yield reduction inside PVGs can be assumed correlated to the available solar radiation according to a rule of thumb, called the “1% rule”, that estimates roughly 1% additional production for each 1% additional light inside the greenhouse (Heuvelink, 2005; Kläring and Krumbein, 2013; Marcelis et al., 2006). An acceptable compromise between horticultural crops and energy production is usually achieved when the PV_R is low (around or lower than 20%), resulting in limited yield losses and negligible impact on the fruit quality. For example, a high demanding crop such as tomato, grown in a PVG with 9.8% of the roof area covered with PV panels, did not show yield reduction due to the shading of the PV panels (Aroca-Delgado et al., 2019; Pérez-Alonso et al., 2012; Ureña-Sánchez et al., 2012). As the PV_R increases, the PVG microclimate becomes affected by the reduced solar radiation to a greater extent, including a decrease of the air temperature and an increase of humidity when ventilation is not applied (Ezzaeri et al., 2018). In addition, the negative effects on growth, development and yield worsen. Plants adopt specie-specific physiological responses to shading that can include shade tolerance or shade avoidance (Gommers et al., 2013). Most species react by optimizing their photosynthetic rate. However, while shade tolerant crops can adjust to lower light levels by optimizing the radiation interception efficiency (RIE), the shade intolerant species (such as tomato) increase their vegetative growth rate and concentrate resources on stem and leaf growth instead of fruits, resulting in lower yield (Smith and Whitelam, 1997).

The PVGs are a major concern in the southern European greenhouse sector, where it is crucial to overcome or mitigate the problems related to cultivation when light is a constraint, in terms of suitable species and agricultural practices (Poncet et al., 2012). Such information is currently scarce in literature and with no general applicability, since it is available only for a limited number of species, cultivated inside specific PVG types. In this paper, the PVGs were considered as options of agricultural management for the chosen species, aimed to identify the best compromise between PVG types and crop planning. For this purpose, we introduced an innovative solar engineering approach based on the comparison between the solar radiation available at canopy level and the crop light requirements. The agricultural compatibility of four PVGs types was evaluated systematically on 14 crops (9 horticultural and 5 floricultural species), classified on the basis of their light requirements (high, medium and low), and estimating the potential yield reduction compared to a conventional greenhouse (CVG). The results identified the PVG types compatible to the cultivation of each considered species and that represent the best compromise between yield and PV_R. In perspective, such findings can be used as a decision-support tool for the greenhouse growers, to adopt the best crop planning and management practices inside PVG agrosystems.

2. MATERIALS AND METHODS

2.1. Solar radiation available inside the photovoltaic greenhouse types

The solar radiation distribution was calculated inside the PVGs using a specific algorithm described in detail in a previous paper (Cossu et al., 2017). The algorithm can calculate the direct (I_D) and diffuse (I_d) radiation and assess when the shadow projected by the PV array cast on specific observation points (OPs) located on the PVG area. When the OPs are under the sunlight, the algorithm attributes both I_D and I_d, resulting in an average global radiation on hourly basis I_{GP} equal to:

$$I_{GP} = \tau \cdot (I_D + I_d) \quad (Wh\, m^{-2}) \qquad [1]$$

where the average greenhouse transmissivity τ is assumed equal to 0.7, considered as a standard value for a common greenhouse. The global radiation inside a CVG (I_G) was assumed always equal to equation [1] throughout the whole year, since no PV array is installed on the roof. On the other hand, when the OPs are under shadow, the algorithm attributes only the diffuse radiation:

$$I_{GP} = \tau \cdot I_d \quad (Wh\, m^{-2}) \qquad [2]$$

I_{GP} was calculated for each PVG type at 1.5 m from the ground level on several OPs, and cumulated on monthly and yearly basis to determine the G_{GR} coefficient, defined as the percentage ratio between I_{GP} and the global radiation inside a CVG (I_G), assuming no PV array installed on the roof:

$$G_{GR} = \frac{\sum_{m=1}^{m=12} I_{GP}}{\sum_{m=1}^{m=12} I_G} \cdot 100 \quad (\%) \qquad [3]$$

where m is the month. The G_{GR} evaluates the effect of the PV array on the roof, compared to the solar radiation inside the hypothetic CVG, where the light condition corresponds to a G_{GR} always equal to 100%, actually optimal for crop production.

The technical specifications of the four commercial PVG types are depicted in Figure 1. All types are located in Italy and they can be considered representative of the situation of the PVG sector in the EU, since similar structures can be found also in France and Spain (Aroca-Delgado et al., 2018; Fatnassi et al., 2015; Poncet et al., 2012). The monthly G_{GR} of all PVG types was already available in literature and reported from a previous work in Figure 2 (Cossu et al., 2018), together with the Coefficient of variation (CV). The CV is the percentage ratio between the standard deviation and the mean, and quantifies the variability of light distribution on the greenhouse area. All structures used opaque multi-crystalline silicon PV panels and had an E-W orientation (PV panels oriented to S). The PVG types can be considered as different light scenarios for the greenhouse crops, classified according to the PV_R, ranging from 25 to 100%:

1. Type 1: Gable roof (PV_R: 25%). Only the top half of the S-oriented roof is covered with PV panels. Polyvinyl chloride (PVC) is used as cladding material;
2. Type 2: Gable roof (PV_R: 50%). The S-oriented roof is entirely covered with PV panels. One of the most diffused types, usually covered with PVC;
3. Type 3: Venlo-type (PV_R: 60%). Usually covered with glass, this particular version of the Venlo-type greenhouse has asymmetric roofs (PV roof oriented to S wider than the glass roof) for enhancing the energy production. The shading on the canopy area is partly counterbalanced by the gutter height higher than the other types (around 4.5 m), to let more light entering from the gable and the side walls;
4. Type 4: Mono-pitched roof (PV_R: 100%). The entire roof area oriented to S is covered with PV panels and the side walls are covered with glass or plastic cladding. This type provides the maximum electric energy production.

2.2. Daily light integral available inside the photovoltaic greenhouse

The light requirements of the greenhouse horticultural and floricultural crops are usually expressed as Daily Light Integral (DLI), that is the average light sum of the photosynthetically active radiation (PAR) received during a day, expressed in mol m^{-2} d^{-1} (Faust, 2002; Torres et al., 2002). Since the coordinates of the studied PVGs had very similar irradiation, the average monthly PAR radiation sum was calculated on the site of PVG type 1 (Decimomannu, Sardinia, Italy, 39°19'59"N, 8°59'19"E) and considered the same for all types. For this location, the average monthly daily irradiation on horizontal plane I_0 was obtained from the European Photovoltaic

Geographic Information System (PVGIS, 2019). The average outside daily PAR radiation sum was expressed using the same unit of the DLI (S_P), calculated for each month according to the following expression:

$$S_P = I_0 \cdot f \cdot 0.0036 \cdot a \quad (mol\, m^{-2}\, d^{-1}) \qquad [4]$$

where f is the fraction of the PAR radiation to the total radiation, assumed equal to 0.48; 0.0036 converts Wh m^{-2} to MJ m^{-2} and a is a coefficient converting the PAR radiation from MJ m^{-2} to mol m^{-2}, equal to 4.57 mol m^{-2} for sunlight. The average daily PAR radiation sum inside a CVG (S_{PC}) was considered equal to:

$$S_{PC} = S_P \cdot \tau \quad (mol\, m^{-2}\, d^{-1}) \qquad [5]$$

To calculate the average daily PAR radiation sum inside the PVG (S_{PG}), the proper G_{GR} was used (depending on the PVG type and the month) and calculated for each month using the equation:

$$S_{PG} = S_P \cdot \tau \cdot G_{GR} \quad (mol\, m^{-2}\, d^{-1}) \qquad [6]$$

The resulting monthly S_{PG} was reported in Figure 2 for all PVG types, including the related external and CVG values, intended as the average on the whole greenhouse area. The S_{PG} was calculated also in the zones of the greenhouse area under the PV and the ST (plastic or glass) roof. In case of PVG type 4, the calculation was conducted on the N and S half greenhouse longitudinal area.

2.3. Daily light integral of greenhouse crops

The proposed methodology compares the global radiation inside a PVG to the light required by the plants. The DLI requirements of 14 common greenhouse horticultural and floricultural crops recommended for good growth and production are reported in Table 1, based on the information available in literature and were not cultivated inside the considered PVG types. The species are classified according to their optimal DLI (DLI_{opt}) in high (DLI_{opt}>30 mol m^{-2} d^{-1}), medium (DLI_{opt} of 10-20 mol m^{-2} d^{-1}) and low (DLI_{opt} of 5-10 mol m^{-2} d^{-1}) light demanding crops (Spaargaren, 2001), assumed constant during the crop cycle. The horticultural crops producing fruits are usually the high light demanding, with minimum DLI necessary for growth (DLI_{min}) of 13 mol m^{-2} d^{-1}, as the average optimal values of the considered high light crops (cucumber, sweet pepper and tomato), which decrease to 9 mol m^{-2} d^{-1} for medium and to 5 mol m^{-2} d^{-1} for the considered low light demanding crops (dracaena, kalanchoe and poinsettia). Between optimal and minimum DLI values, the solar radiation is fair or good for cultivation, ensuring good yield and quality.

The yield variation (for horticultural species) or fresh mass (for floricultural species) as a function of light was estimated through the 1% rule, thus a rule of thumb establishing that 1% additional light results in 1% increase of the yield (Kläring and Krumbein, 2013; Marcelis et al., 2006). Depending on the species, the percentage of yield variation of fresh yield follows ranges that can be lower or higher than 1% (Table 1). To facilitate the yield estimations, the variation of fresh yield of each specie was calculated using the mean value of its range (V_c), which is assumed constant during the crop cycle. The yield reduction was estimated by using its complementary value to one, or rather a yield factor (Y_f) that estimates the average percentage of the crop production inside the PVG, compared to the CVG:

$$Y_f = \left[1 - \frac{(S_{PC} - S_{PG}) \cdot V_c}{S_{PC}}\right] \cdot 100 \quad (\%) \qquad [7]$$

The formula assumes Y_f equal to 100% inside a CVG, where the light conditions can be considered optimal or good for all crops (PAR radiation sum S_{PC} equal to 24.4 mol m^{-2} d^{-1}) and decreases it proportionally to V_c inside the PVG types, in which the PAR radiation sum of the PVG (S_{PG}) is lower. This is valid for high demanding crops, when $DLI_{opt} > S_{PG}$. For lower light demanding crops, the S_{PG} may be already optimal for cultivation and the Y_f starts decreasing from lower PAR radiation sums, according to equation [8]:

$$Y_f = \left[1 - \frac{(DLI_{opt} - S_{PG}) \cdot V_c}{DLI_{opt}}\right] \cdot 100 \quad (\%) \qquad [8]$$

Since the global radiation inside PVGs is often lower than a CVG, a maximum yield reduction of 25% was assumed acceptable for assessing the agricultural sustainability of PVGs for crop production, corresponding to a yearly minimum Y_f of 75%.

3. RESULTS

3.1. Yield estimation inside photovoltaic greenhouses

The solar radiation distribution is heterogenous on the greenhouse area due to the shading of the PV panels, as shown by the CVs on monthly and yearly basis (Figure 2). The average CV generally increases with the PV_R: the yearly CV ranges from 31% of type 1 to 60% of type 4, indicating that a low PV_R is preferable also to avoid excessive heterogeneity of light distribution, that may affect negatively the uniform growth and development on the greenhouse area. An exception is type 3, with a yearly CV lower than type 1 and 2 (38%), due to its higher gutter height, that contributes to a better light distribution. As the PV_R increases, higher fluctuations of the monthly CV can be observed, particularly inside PVG type 4 (ranging from 51 to 92%), whereas the light distribution of PVG type 1 was more uniform, with a CV that ranged from 40% in December to 47% in September.

The agricultural compatibility of the light scenarios inside the PVGs toward the considered crops was depicted in Figure 3. The graphs compared the light requirements of the crops in terms of DLI to the yearly S_{PG} inside the four PVG types. This methodological approach allowed to assess easily which PVG types were suitable for the considered species, based on the estimation of their potential yield, compared to CVGs. The results of the assessment were divided according to the crop light requirement classes (high, medium and low).

3.1.1 High light demanding species

Tomato, cucumber and sweet pepper are high light demanding species that found an optimal light condition for crop production ($Y_f \geq 75\%$ compared to a CVG) only inside PVG type 1 (PV_R 25%), where the average Y_f is around 80 and 79% for tomato and cucumber, respectively, and 75% for sweet pepper (Fig. 3a). The Y_f was lower than 75% under the PV roof (yield reduction higher than 25%), ranging from 47 to 57% for sweet pepper and tomato, respectively. This difference was due to the heterogeneity of light distribution at canopy level (difference between the light under the PV and ST roof). The Y_f of tomato was consistent with observations conducted inside a PVG with 10% of the total roof area covered with flexible PV panels, where no negative effects on yield, height and stem diameter were detected (Ezzaeri et al., 2018). In addition, the PV panels inhibited the development of the population of the tomato leafminer (*Tuta absoluta* M.). The limited and tolerable yield losses should become lower or negligible when the PV_R decreases, as already shown on tomato and sweet pepper with PV_R ranging from 9.8 to 20%, where no negative effects were noticed on the yield and quality, including no decrease of lycopene, phenolic or antioxidant concentration (Ezzaeri et al., 2018; Kavga et al., 2018; Minuto et al., 2011; Trypanagnostopoulos et al., 2017; Ureña-Sánchez et al., 2012). Previous observations on pepper grown inside an agricultural greenhouse with a PV_R of 20% showed an increase of fresh weight, leaf area and chlorophyll content (Hassanien and Ming, 2017; Trypanagnostopoulos et al., 2017).

PVG type 2 (PV_R 50%) is a light scenario not recommended for all considered high light demanding species (Fig. 3b): tomato suffered a Y_f of only 61%, corresponding to a yield reduction of 39%, whereas cucumber showed an average Y_f of 59%. This is consistent with what observed in a PVG with a PV_R of 50% in Italy, where the yearly marketable production of tomato was 5.8 kg m^{-2}, that is 42% less than the average yield of tomato in Southern Italy, which is around 10 kg m^{-2} (Cossu et al., 2014). Furthermore, negative effects on lycopene and sugar content were observed in another Italian PVG with the same PV_R (Bulgari et al., 2015). The production under the ST roof of PVG type 2 can be considered satisfactory for tomato and cucumber, with a Y_f of 78 and 77%, respectively. The heterogenous light distribution on the greenhouse area caused a low yield under the PV roof (Y_f below 75%), that amounted to 31 and 41% for sweet pepper and cucumber, respectively. A linear yield reduction of tomato was detected applying an aluminized shade cloth with a shading ranging from 15 to 50%, but increased the marketable fraction (less incidence of fruit cracking), whereas low or negligible yield losses were noticed with shading levels of 15 and 30% (Gent, 2007). A similar trend was described on tomato inside a greenhouse with 52% shading nets, where the growth reduced by 21.7%, as well as the fruit and vegetative dry mass, with an increase of the leaf area index (LAI) (Sandri et al., 2003). Plants under limiting DLI conditions typically show delayed growth and development, with yield and quality reduction that should discourage the grower from cultivation or suggest the use of supplementary lighting (Faust and Logan, 2018). Shading triggers shade-avoidance strategies on tomato, including the increase of LAI, with a consequent increase of the light use (LUE) and interception efficiency (RIE) (Kläring and Krumbein, 2013).

PVG type 3 and 4 resulted incompatibles for cultivation of high light demanding species, with an average Y_f ranging from 57% of tomato inside PVG type 3, to only 26% of sweet pepper inside PVG type 4 (Fig. 3c and 3d). High yield losses are expected (up to 75% for sweet pepper) from these PVG types, underlining their overall agricultural unsustainability.

3.1.2 Medium light demanding species

Most of the considered medium light demanding horticultural crops can be cultivated inside PVGs from type 1 to 2 with limited yield losses (below 25%). An exception was lettuce, since the cultivation inside PVG type 2 led to an average Y_f of 73%. Strawberry showed an average Y_f of 76% with a PV_R of 50%, even though this latter crop could perform better than predicted. Indeed, wild strawberry, blueberry and raspberry inside PVGs with 32 and 100% PV_R resulted in an increase of the antioxidant activity of the fresh produce, including total anthocyanins, citric and fumaric acid (Blando et al., 2018). The difference between the Y_f of lettuce under the PV and ST roof is considerable, since the estimated yield reduction inside PVG type 2 ranged from 8% under the ST roof to 47% under the PV roof. The average Y_f of lettuce inside PVG type 1 and 2 (94 and 73%, respectively) was consistent with experimental trials inside agrivoltaic systems with 25 and 50% PV_R (corresponding to 70 and 50% of the total PAR), where lettuce showed a Y_f of respectively 99 and 79% of the control crop (Marrou et al., 2013b). The higher values are possibly due to the microclimatic differences between PVGs and agrivoltaics, the latter being open-field systems (Marrou et al., 2013). Lettuce compensated the limiting PAR by increasing the RIE with physiological adjustments, including a different leaf arrangement (reduction of the leaf angle), a decrease of the leaf number coupled to a higher total leaf area and head diameter, that resulted in limited or none yield reduction. The results inside PVG type 1 are in agreement with the current literature, that reported no significant effects of the PV panels on the yield of basil, when 19% of the roof area was covered (Minuto et al., 2009). Inside the same PVG, strawberry and lettuce completed the cycle earlier than the crops in the control greenhouse (Minuto et al., 2011). A PV_R of 20% or lower did not result in yield or growth reduction (Hassanien and Ming, 2017; Kavga et al., 2018; Trypanagnostopoulos et al., 2017). In addition, oidium (*Oidium neopycopersici*) affected tomato more in the PVG than the control greenhouse. The increase of fungal diseases is frequently diagnosed in crops inside PVGs, due to the higher air humidity and the reduced ventilation at canopy level (Jacob et al., 2008). Furthermore, crops often show an increase of nitrate content, especially leafy vegetables, where the low light intensity leads to a disproportion between the nitrate ion uptake and reduction, with a consequent accumulation in the leaves (Khan et al., 2018; Santamaria, 2006).

The medium light demanding floricultural crops showed a good compatibility with PVG from type 1 to 2. An exception is rose, which showed an average Y_f higher than 75% only inside PVG type 1 (94%). However, it is known that rose benefits from moderate shading during parts of its cycle, as observed in a greenhouse with shading nets up to 50% that contributed positively to the quality parameters of the petals, in terms of protein, carbohydrate and anthocyanin content (Hatamian and Salehi, 2017). Finally, none of medium light species can be profitably cultivated inside PVG type 3 and 4, where Y_f was abundantly lower than 75% (except asparagus and ficus with a Y_f of 75 and 84% respectively, inside PVG type 3). This information are supported by experimental trials on the rocket (*Diplotaxis tenuifolia* L.) grown inside a PVG with 100 PV_R, which showed a reduction of dry matter and yield of 84% compared to the control greenhouse with polycarbonate cladding, even if it can benefit from some shading throughout the year (Buttaro et al., 2016; Hall et al., 2012). In addition, it showed a leaf nitrate content 13 times higher (about 10,000 mg kg^{-1} of fresh weight) than the control, which is far above the EU Regulation limit of 7,000 mg kg^{-1} of fresh weight (European Commission, 2011), resulting in an unmarketable production.

3.1.3. Low light demanding species

All the considered floricultural low light demanding species (dracaena, kalanchoe and poinsettia) showed an average Y_f of at least 75% inside all PVG types analysed, disregarding of the PV_R and the heterogeneity of light distribution on the greenhouse area. As a consequence, all PVG types can be considered suitable for their cultivation. Indeed, the considered ornamental plants require extensive shading inside CVGs during periods of intense irradiation (Faust, 2002; Spaargaren, 2001), that is supposed to be deployed also in PVGs to ensure proper growth and quality. Other low light demanding flowers such as Iberis (*Iberis sempervirens* L.) and Petunia (*Petunia grandiflora*) grown inside PVG with a PV_R of 20% did not show significant effects on the vegetative growth (Colantoni et al., 2018). In general, floricultural crops can be considered more suitable for cultivation inside PVGs than the horticultural ones, also considering their need for moderate or occasional shading, especially in hot and sunny regions, where the natural irradiation can be excessive and partly used to produce electrical energy through the PVG (Ahemd et al., 2016; Yano et al., 2014). Other studies proposed edible mushrooms as suitable crops inside Chinese solar greenhouses with high PV_R, with profitable yield levels (Li et al., 2017).

3.2. Monthly light distribution on the photovoltaic greenhouse area

The average monthly S_{PG} is depicted in Figure 4. Remarkable differences were observed under the PV and the ST roof of PVG type 1 and 2 from April to September (Fig. 4a and 4b). These types showed monthly S_{PG} values compatible with all the considered species for most of the year (except winter months) and yearly S_{PG} under the ST roof of 20.2 and 18.1 mol m^{-2} d^{-1}, respectively, with peaks of 35.3 and 36.4 mol m^{-2} d^{-1} in June. On the contrary, the yearly S_{PG} under the PV roof was considerably lower (12.2 and 8.3 mol m^{-2} d^{-1} respectively for PVG type 1 and 2) and did not meet the DLI_{min} of the considered high light demanding crops (13 mol m^{-2} d^{-1} on average), especially during the summer months.

PVG type 3 and 4 were characterised by an average S_{PG} lower than type 1 and 2 and with less variability between PV and ST roofs (Fig. 4c and 4d). PVG type 3 showed a S_{PG} of 9.7 mol m^{-2} d^{-1} under the ST roof (with peak in June of 14.4 mol m^{-2} d^{-1}), and 13.5 mol m^{-2} d^{-1} under the PV roof, with the maximum in August (20.3 mol m^{-2} d^{-1}). The average S_{PG} was slightly higher than the DLI_{min} of the high light demanding crops from May to August, suggesting to avoid such crops on both winter and summer cycles. On the other hand, medium and low light demanding crops are compatible with cultivation also under the PV roof, where the yearly S_{PG} is actually higher than the average DLI_{min} of the considered medium light crops (9 mol m^{-2} d^{-1}). Finally, PVG type 4 showed the lowest average S_{PG} (7.1 mol m^{-2} d^{-1}) compatible only with the DLI_{min} of low light demanding crops (5 mol m^{-2} d^{-1}) on the whole PVG area (Fig. 4d).

4. DISCUSSION

4.1. Photovoltaic greenhouse types compatible with crop production

While the estimated yield of high light demanding species under the ST roof was generally acceptable (Y_f above 75%), the reduction was remarkable under the PV roof, as confirmed by previous experiments that highlighted the negative effects on the plant physiology such as tomato, where an increase of LAI and a reduction of the stomatal conductance, growth, photosynthetic and transpiration rate occurred, observed also on lettuce (Marrou et al., 2013a; Sirigu et al., 2013). The photosynthetic and growth rate are highly correlated to the available PAR radiation (Heuvelink, 1995). In particular, the photosynthetic rate of tomato inside a PVG type 2 was considerably lower than the CVG, which can affect the transpiration and cause limitations on water absorption and physiological disorders due to nutritional deficiencies (Cossu et al., 2017a).

In general, the medium light demanding crops with a DLI_{opt} equal or lower than 17 mol m^{-2} d^{-1} are supposed to achieve good average yield (Y_f >75%) with a PV_R up to 60%. Therefore, they should be considered for further experimental trials aimed to assess their yield and economic profitability, especially ficus and asparagus. This latter specie (white asparagus) is promising because it can adapt well to the poor light conditions under PV panels (Sgroi et al., 2014; Tudisca et al., 2013) and it showed a Y_f also of 75% also inside PVG type 3 with a PV_R of 60%.

All PVG types resulted suitable for the cultivation of the low light demanding species. These overall results suggest that all crops with a DLI_{opt} equal to or lower than 10 mol m^{-2} d^{-1} can be cultivated inside all PVG types, resulting in limited or negligible yield reductions. Additional experimental trials are required to confirm the present estimations and the effects of persistent shading on the plant development and management, especially inside PVG type 4 (PV_R of 100%).

4.2. Crop cycle management inside photovoltaic greenhouses

The monthly light distribution inside the PVG suggest the implementation of alternative crop management strategies that identify the proper periods to start the crop cycle, allowing the plants to find the best light conditions during their growth and development stages. For example, the cycle of basil is 30 days long on average, allowing up to 10 cycles per year in a CVG (Fritegotto, 2012). According to the yearly trend of S_{PG} inside PVGs type 1 and 2 (Fig. 4a and 4b), it is possible to complete a similar number of cycles during the year, whereas for PVG type 3 the number is supposed to be lower and should be concentrated in spring and summer, since the winter cycles would find barely sufficient light conditions (Fig. 4c). According to the mentioned results, the crop cycles can be concentrated in the central part of the year, avoiding the PVGs zones where the solar radiation is limiting or insufficient (PV roofs), or choosing lower light demanding species. Such practices can be applied reasonably only on short cycle crops, such as leafy vegetables, which can be transplanted when the S_{PG} is optimal for the whole plant cycle. On the other hand, crops with a 6-month cycle or longer (such as tomato or sweet pepper) actually lose the possibility to conduct two cycles per year if the transplant is postponed to skip the winter months, suggesting to choose crops with lower light requirements and shorter cycles. This latter consideration is almost mandatory inside PVGs with a PV_R equal or higher than 50%, or risk delaying the harvest and losing a considerable part of the production.

The heterogeneity of light distribution at canopy level highlighted that average S_{PG} values on the greenhouse area compatible for crop production could result in insufficient values under the PV roofs, leading to different photosynthetic and transpiration rates among the plants rows under PV and ST roofs. These aspects should be managed by choosing crops able to maintain a high photosynthetic/transpiration ratio during the transition periods between light and shade, and able to cover the ground area quickly to enhance the water use efficiency (Marrou et al., 2013a). In fact, lower transpiration rates can determine a waste of fertigation solution that can be prevented by implementing fertigation systems with different flow rates to the plant rows, to avoid an excess of nutrient solution under the PV roof and a water and nutrient stress on the rows under the ST roof (Cossu et al., 2017a; Deligios et al., 2017). For this reason, the crop planning and the application of precision fertigation systems might allow the cultivation of two species or varieties inside the same PVG module, differentiating the distribution of the fertigation solution among the plant rows, as a function of their specific transpiration rates. For example, inside PVG type 1 and 2 a high light (i.e. tomato) and a medium light demanding specie (i.e. lettuce) could be grown under the ST and the PV roof, respectively, implying differentiated crop management practices (especially fertigation and crop protection) among and within species. Such strategies can be applied to increase the compatibility of PVGs to crops that are usually not productive under high PV_R and contribute to increase and diversify the income of the farm.

4.3. Reconversion of photovoltaic greenhouses to innovative agrosystems

The PVGs are characterised by a high potential in establishing modern and sustainable energy self-sufficient agrosystems, once the best trade-off between energy and crop production is achieved, through the right choice of the species and transplantation periods. The present work identified the PVG types resulting in the highest possible yields for the considered species, supporting the identification of this compromise, even though PVG types with high PV_R (around 100%) resulted unsustainable for horticultural crops. According to this, further strategies to reconvert the existing PVGs to sustainable cropping systems should be considered, by offering innovative management options to the growers, including the controlled environment technologies and the precision agriculture. In particular, a radical requalification is necessary for the PVG types with PV_R of 100%, by compensating the persistent shading with specific high efficient supplementary lighting systems.

Previous studies underlined the inappropriateness of the high pressure sodium (HPS) lamps applied to a conventional hydroponic tomato crop inside PVGs with a PV_R of 50%, even when powered by PV energy, because the energy consumed by the lamps can easily exceed the energy production of the PV system and does not sort substantial beneficial effects (Cossu et al., 2014). However, the energy efficiency of artificial lighting performed with light emitting diodes (LED) is spreading in vertical farming systems and plant factories to producing functional fresh food through sustainable and competitive cropping systems with reduced CO_2 emissions and minimum use of resources, with 30-40% energy saving compared to previous generation lamps, up to 95% reduction of water and up to 100% of pesticides (Kikuchi et al., 2018; Kozai, 2018, 2013). The possibility to customize the light quality with LEDs allows to save energy and supply only specific light wavelengths (especially in the red, far red and blue interval) that enhances the production of high-quality and growing-demand fresh food with specific compounds beneficial for human health (nutraceutical food), such as natural antioxidants and essential oils (Chang et al., 2008; Demotes-Mainard et al., 2016; Piovene et al., 2015; Samuolienė et al., 2012). In fact, LEDs can be customized to produce specifically the wavelengths that maximise the production of the desired nutraceutical compounds compared to CVG cropping systems, in order to produce fresh food (usually leafy vegetables, seedlings, transplants and herbal medicines) or biomass to be processed for the extraction, such as dietary supplements (Kozai, 2013). The advantages of these innovative systems are the saving of resources, the high yield, quality and durability against adverse weather conditions (Campiotti et al., 2008; Kikuchi et al., 2018; Yano and Cossu, 2019). However, the main drawback is the cost of the energy required for operation, that should be supplied by the PV source to ensure the economic and environmental sustainability of the system.

Given the abundant PV energy available in PVGs with PV_R around 100%, the use of LED lighting could be economically feasible when applied to vertical farming systems, because lights are close to the plants, ensuring maximum efficiency of the lighting sessions and quality of the fresh produce. This solution could result in satisfactory yield and added value of the products, that is a sustainable compromise for both energy and horticultural production. On the other hand, the application of these systems to PVG types with a PV_R around 50% is not essential (medium and low light demanding species can be successfully cultivated without supplementary lighting), but it would allow the cultivation of high light demanding crops and contribute to their higher agronomic productivity and quality. Finally, light scenarios with a PV_R around 25% do not require a reconversion to vertical farming, since all crops can be grown with limited or none yield reduction.

The renewable energy produced by PVGs could be valorized with the vertical farming technologies, although to date there are no applications of this innovative and alternative cropping system to PVGs in literature. Feasibility studies are necessary to demonstrate their technical and economic performance in this specific context. This emerging and highly promising market could justify the use of the PV energy to supply electricity for the LED lamps, leading PVGs to become sustainable and energy efficient agrosystems for local, functional and organic fresh food production.

5. CONCLUSIONS

Choosing and managing crops able to adapt to the light conditions of PVGs is still a thorny issue for the greenhouse growers and researchers, especially for PVG types with high PV_R. In this paper, we discussed the yield estimations and the crop planning of 14 horticultural and floricultural crops inside four common PVG types in Europe, compared to conventional greenhouses. An original method comparing the light scenarios inside PVGs and the crop light requirements was applied, to estimate the yield and the best periods to start the crop cycle, compared to conventional greenhouses. All the considered species (including high light demanding crops) can be cultivated inside PVGs with 25% PV_R showing limited yield reductions (below 25%), but restrictions on growth and yield occurred when the PV_R raised from 50 to 100%. Medium light demanding horticultural species with an optimal DLI lower than 17 mol m^{-2} d^{-1} (such as asparagus) can be grown inside PVGs with a PV_R up to 60%. Low light species with an optimal DLI equal to or lower than 10 mol m^{-2} d^{-1} can be cultivated inside all considered PVG types (including PVGs with 100% PV_R) with negligible or limited yield reduction, such as poinsettia, kalanchoe and dracaena. The heterogeneity of light distribution inside PVGs (difference between the global radiation under the

PV and the ST roofs) should be considered carefully for the crop management, especially in terms of fertigation, crop protection and transplantation period among the plant rows. To achieve good yield and profit levels, PVGs with high level of PV cover ratios (around 100%) should consider a reconversion by implementing innovative agrosystems provided with LED lighting (such as the vertical farming) able to foster the production of high-quality fresh food with an added functional and economic value on the market. Tackling the agricultural sustainability issues of the present structures is the key to plan the future of the PVG sector. This study is a first attempt to provide original and general decision-support information on the potential trade-off between crop planning and PVGs types aimed to improve the agricultural sustainability and profitability of PVG systems.

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Figures and tables

PV greenhouse types	1	2	3	4
	25% Gable roof	50% Gable roof	60% Venlo-type	100% Mono-pitched roof
External view				
Location	*Decimomannu 39°19'59"N, 8°59'19"E*	*Decimomannu 39°19'51"N, 8°59'27"E*	*Villasor 39°22'23"N, 8°55'29"E*	*Florinas 40°38'38"N; 8°39'31"E*
PV cover ratio (PV_R)	*25%*	*50%*	*60%*	*100%*
Actual PV_R	*25.5%*	*47.8%*	*61.8%*	*96.9%*
Orientation	*E-W*	*E-W*	*E-W*	*E-W*
Dimensions (W x L)	*9.6 x 50.0 m*	*9.6 x 50.0 m*	*8.4 x 100.0 m*	*9.0 x 93.0 m*
Area	*480 m^2*	*480 m^2*	*840 m^2*	*837 m^2*
Gutter height	*2.5 m*	*2.5 m*	*4.5 m*	*2.5 m*
Roof slope	*22°*	*22°*	*26°*	*20°*
Cladding material	*Plastic (PVC)*	*Plastic (PVC)*	*Glass*	*Glass*
Number of modules	*98*	*150*	*400*	*696*
PV system rated power	*20 kWp*	*35 kWp*	*94 kWp*	*132 kWp*
GREENHOUSE FARM				
Total PV power	*1 MWp*	*1 MWp*	*2 MWp*	*3 MWp*
Total covered area	*3.5 Ha*	*3.5 Ha*	*2.5 Ha*	*2 Ha*

Figure 1. Specifications of the considered commercial PVG installations located in Sardinia (Italy) (modified from Cossu et al., 2018). The dimensions are referred to one PVG module and the total area and PV power of the farm are also reported. PVG type 1 and 2 are located in the same farm.

Months	S_P *(mol m^{-2} d^{-1})*														
		CVG		***Type 1 (25%)***			***Type 2 (50%)***			***Type 3 (60%)***			***Type 4 (100%)***		
		G_{GR}	S_{PC} *(mol m^{-2} d^{-1})*	G_{GR}	S_{PG} *(mol m^{-2} d^{-1})*	*CV*	G_{GR}	S_{PG} *(mol m^{-2} d^{-1})*	*CV*	G_{GR}	S_{PG} *(mol m^{-2} d^{-1})*	*CV*	G_{GR}	S_{PG} *(mol m^{-2} d^{-1})*	*CV*
January	16.0		11.2	74%	8.3	44%	45%	5.0	65%	72%	8.0	43%	45%	5.0	63%
February	21.3		14.9	72%	10.8	45%	46%	6.8	65%	59%	8.8	59%	40%	5.9	77%
March	32.4		22.7	74%	16.8	46%	49%	11.2	76%	50%	11.4	61%	30%	6.7	87%
April	42.0		29.4	77%	22.5	42%	55%	16.3	69%	47%	13.8	57%	26%	7.5	84%
May	48.8		34.2	78%	26.7	43%	57%	19.4	65%	44%	14.9	51%	24%	8.3	51%
June	55.4	100%	38.8	78%	30.3	41%	62%	23.9	57%	41%	15.9	47%	25%	9.8	57%
July	54.4		38.1	78%	29.8	42%	60%	22.7	58%	43%	16.3	50%	26%	9.8	52%
August	49.2		34.4	77%	26.5	44%	56%	19.2	69%	47%	16.0	55%	24%	8.2	69%
September	38.7		27.1	75%	20.4	47%	52%	14.0	76%	49%	13.2	59%	28%	7.7	92%
October	27.6		19.3	73%	14.0	45%	45%	8.7	70%	55%	10.6	62%	36%	7.0	77%
November	18.0		12.6	73%	9.2	44%	45%	5.7	65%	69%	8.6	47%	43%	5.5	67%
December	14.4		10.1	76%	7.7	40%	46%	4.6	61%	77%	7.7	39%	47%	4.8	58%
Yearly mean	**34.8**	**100%**	**24.4**	**76%**	**18.6±5.8**	**31%**	**54%**	**13.2±7.0**	**53%**	**49%**	**12.0±4.5**	**38%**	**29%**	**7.1±4.3**	**60%**

Figure 2. Yearly solar radiation inside the four PVG types compared to a CVG, expressed as G_{GR} (%) available in literature (Cossu et al., 2018). The coefficient of variation (CV) expressed as percentage is also reported. Data is referred to a height of 1.5 m above the ground level, with average $\tau = 0.7$. The monthly PAR sum was calculated outside (S_P), inside the CVG (S_{PC}) and the PVG (S_{PG}) in mol m^{-2} d^{-1} using the irradiation data of the PVG type 1 site (Decimomannu, Sardinia, Italy, 39°19'59"N, 8°59'19"E), retrieved from the solar photovoltaic energy web calculator (PVGIS, 2019) and corrected with the G_{GR} coefficients of the PVG types according to Eq. [6]. The yearly sum reports also the standard deviation.

Table 1. Daily light requirements (DLI) of 14 common horticultural and floricultural greenhouse crops. The variation range of fresh production as a function of 1% additional/less solar light (1% rule) are shown, including the mean value of the range (V_c). Species are listed in alphabetical order, according to the DLI demand class (high, medium and low).

Species	***DLI crop requirements (DLI_C, mol m^{-2} d^{-1})***			***Variation in fresh yield with 1% additional light (%)***	***Mean R_c (%)***	***Reference***
	Insufficient (DLI_{Cmin})	***Sufficient/Good***	***Optimal (DLI_{Copt})***			
High light demanding: DLI_{Copt}>30 mol m^{-2} d^{-1}						
Cucumber (*Cucumis sativus*)	<12.0	12.0-30.0	>30.0	0.6-1.2	0.90	(Dorais, 2003; Fisher and Runkle, 2004; Marcelis, 1993; Spaargaren, 2001)
Sweet pepper (*Capsicum annuum*)	<12.0	12.0-30.0	>30.0	0.8-1.3	1.05	(Dorais, 2003; Fisher and Runkle, 2004; Nilwik, 1981; Spaargaren, 2001)
Tomato (*Solanum lycopersicum*)	<15.0	15.0-30.0	>30.0	0.6-1.1	0.85	(Cockshull et al., 1992; Dorais, 2003; Fisher and Runkle, 2004; Heuvelink, 1995; Marcelis et al., 2006; Spaargaren, 2001)
Medium light demanding: DLI_{Copt} 10-20 mol m^{-2} d^{-1}						
Asparagus (*Asparagus officinalis*)	<6.5	6.5-16.7	>16.7	0.8-1.0	0.90	(FLL, 1995; Marcelis et al., 2006; Spaargaren, 2001)
Basil (*Ocimum basilicum*)	<5.3	5.3-17.3	>17.3	0.8-1.0	0.90	(Dou et al., 2018; Marcelis et al., 2006)
Lettuce (*Lactuca sativa*)	<12.0	12.0-20.0	>20.0	0.8	0.80	(de Koning, 1989; De Pinheiro Henriques and Marcelis, 2000; Glenn et al., 1984; Melissa Brechner and David De Villiers, 2013; Fisher and Runkle, 2004; Spaargaren, 2001)
Strawberry (*Fragaria ananassa*)	<12.0	12.0-19.0	>19.0	0.6-1.0	0.80	(Fisher and Runkle, 2004; Marcelis et al., 2006)
Spinach (*Spinacia oleracea*)	<8.0	8.0-17.0	>17.0	0.9	0.90	(de Koning, 1989; De Pinheiro Henriques and Marcelis, 2000; Glenn et al., 1984; Melissa Brechner

						and David De Villiers, 2013)
Chrysantemum (*Chrysantemum morifolium*)	<10.0	10.0-20.0	>20.0	0.3-1.0	0.65	(Faust, 2002; Lee et al., 2003)
Rose (*Rosa chinensis*)	<10.0	10.0-20	>20.0	0.8-1.0	0.90	(Faust, 2002; Marcelis, 1993; Zieslin and Mor, 1990)
Ficus (*Ficus benjamina*)	<8.0	8.0-16.0	>16.0	0.65	0.65	(Faust, 2002; Marcelis et al., 2006; Mortensen and Grimstad, 1990)
Low light demanding: DLI_{Copt} 5-10 mol m^{-2} d^{-1}						
Dracaena (*Dracaena fragrans*)	<4.0	4.0-8.0	>8.0	0.65	0.65	(Faust, 2002; Marcelis et al., 2006)
Kalanchoe (*Kalanchoe blossfeldiana*)	<4.0	4.0-8.0	>8.0	0.8-1.0	0.90	(Gislerød et al. 1989; Faust 2002; Marcelis et al. 2006)
Poinsettia (*Euphorbia pulcherrima*)	<6.0	6.0-10.0	>10.0	0.5-0.7	0.60	(Faust, 2002; Marcelis et al., 2006)

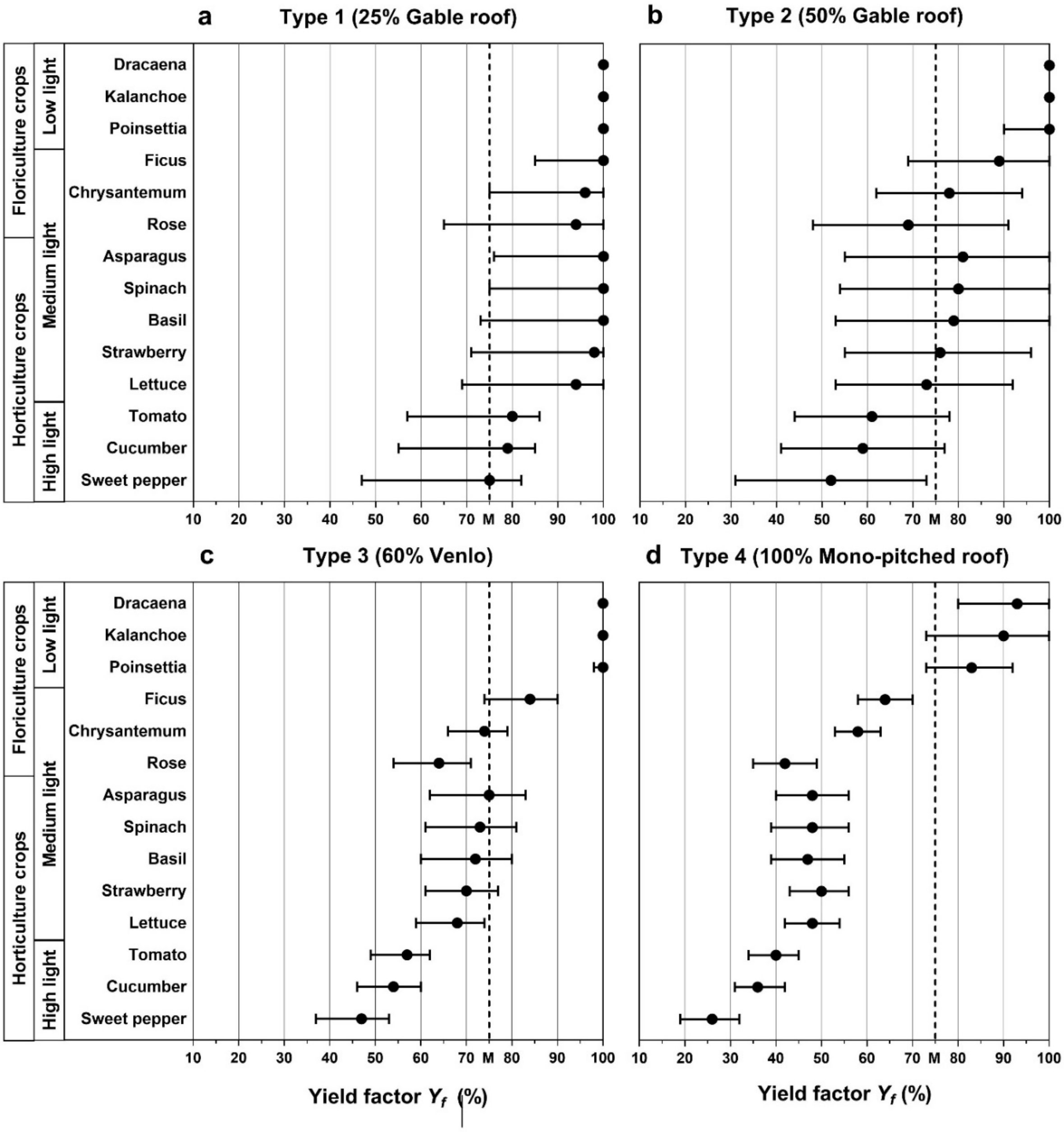

Figure 3. Agricultural compatibility of the four PVG types towards the considered crops, classified according to their DLI. The value M on the x axis is the minimum Y_f acceptable on yearly basis (75%). The error bars represent the Y_f under the PV roof (low bars) and the ST (glass or plastic) roof (high bars). As for PVG type 3 (PV_R 60%), the bars have opposite meaning (low bars are the Y_f under the glass roof and the high bars under the PV roof), because of the specific light distribution of this type, while for PVG type 4, the high and low error bars represent the Y_f respectively under the S and the N half of the greenhouse area.

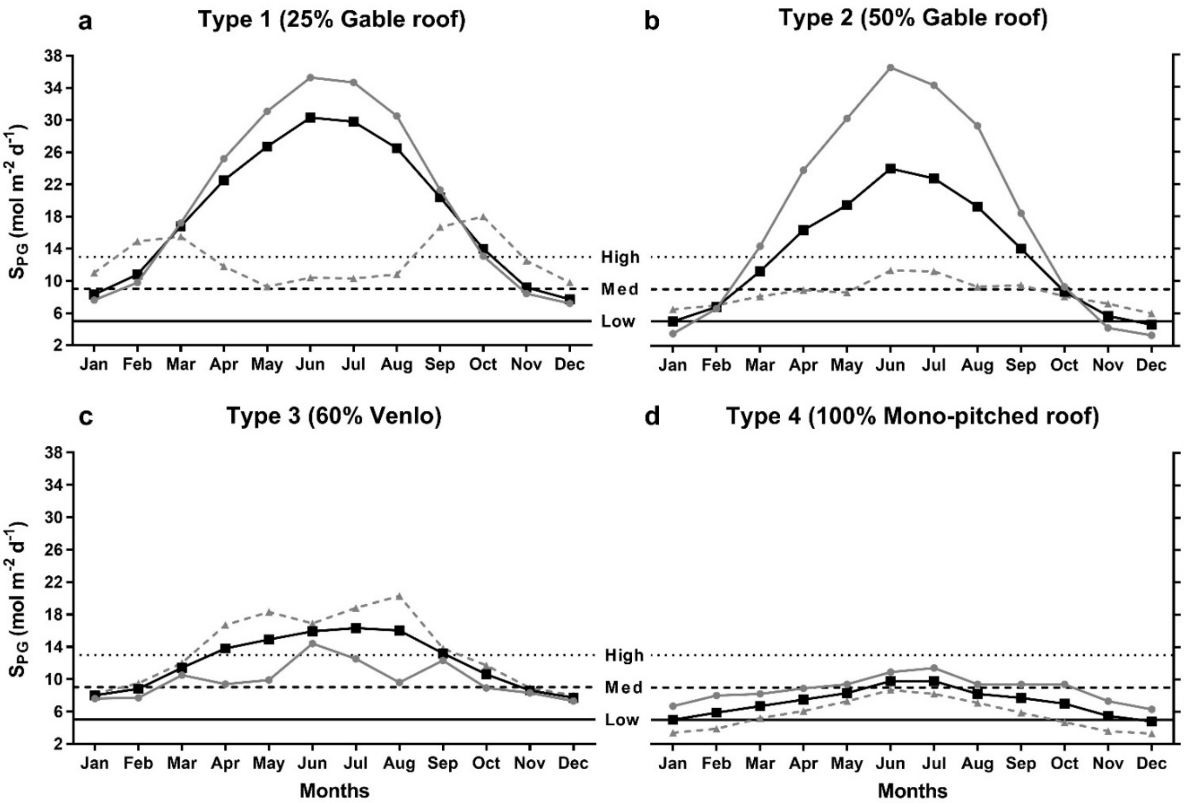

Figure 4. Average monthly S_{PG} inside the four PVG types, compared to the average DLI_{min} requirements of the species considered in the study: high (min. 13 mol m^{-2} d^{-1}), medium (min. 9 mol m^{-2} d^{-1}) and low light demanding crops (min. 5 mol m^{-2} d^{-1}). The average S_{PG} of the whole PVG area is reported (black lines and squares), together with the S_{PG} under the conventional (ST) roof (grey lines and circles) and the photovoltaic (PV) roof (grey dotted lines and triangles). For PVG type 4 (PV_R 100%), the PV and the ST roof correspond to the N-half and the S-half greenhouse area, respectively.